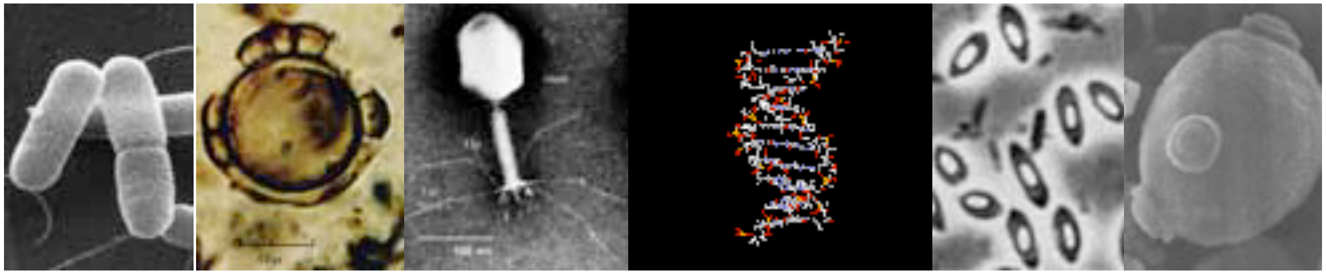


Chemistry of life

General Microbiology - Lecture 2

Cañada College, Redwood City - Fall 2008

Instructor: Tamas Torok, Ph.D.

Topics for today

- (Very) basic chemistry terms
- Biologically important
  - bonds
  - reactions
  - molecules/polymers/macromolecules

Unity of life

- Cellular organization
  - cell - a dynamic entity that forms the fundamental unit of life
- Same macromolecules do basically the same chemical processes in an open, non-equilibrium system
- Living organisms accumulate and recycle elements of their environment

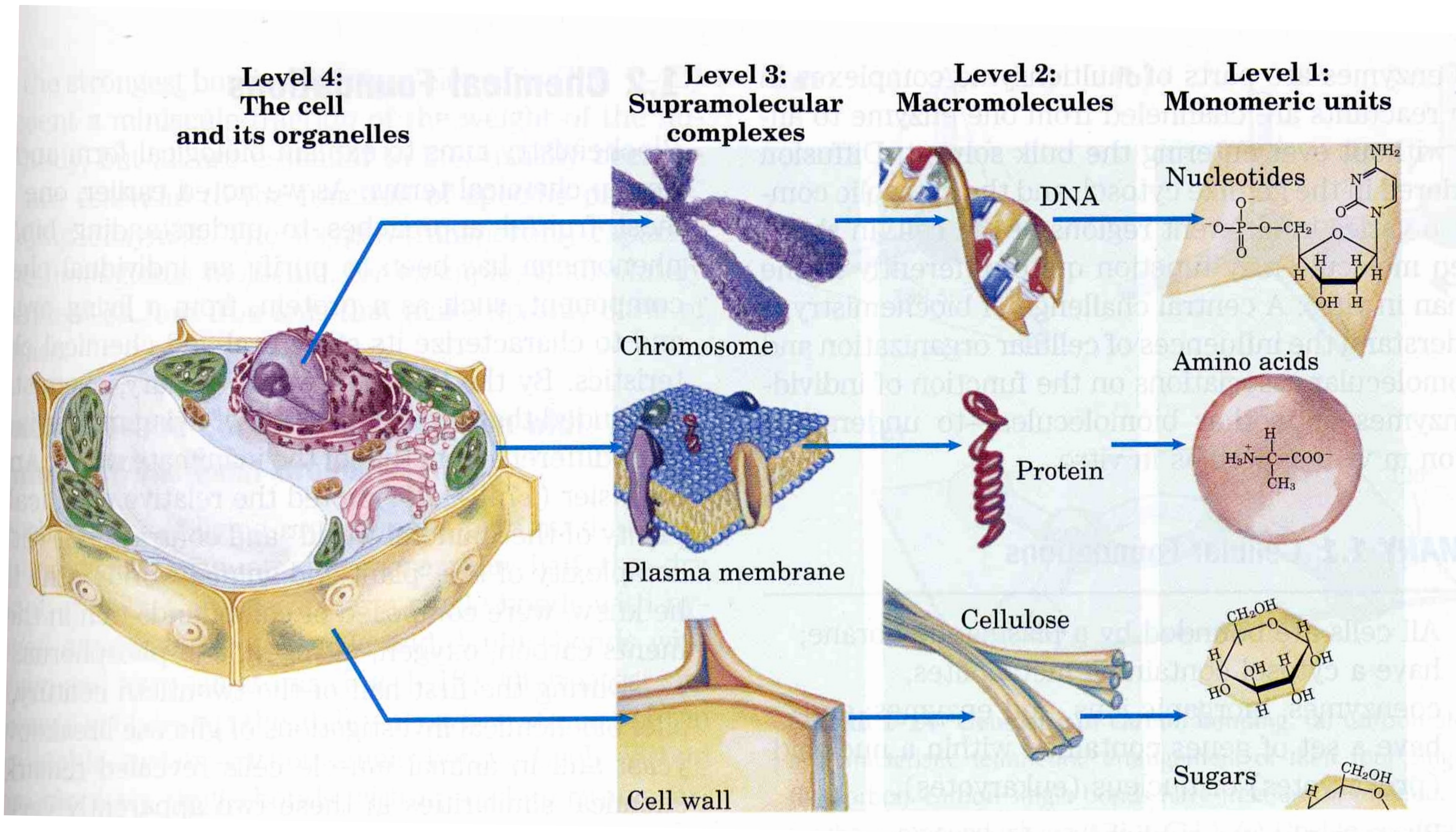
Characteristics of living systems

- **Compartmentalization and metabolism**
  - chemical transformation of nutrients
- **Regeneration**
  - repair and replacement of components
- **Reproduction**
  - generation of two cells from one
- **Differentiation**
  - synthesis of new substances or structures that modify the cell (only in some microbes)

Characteristics of living systems

- Communication
  - generation of, and response to, chemical signals
- Movement
  - via self-propulsion, many forms in microbes
- Evolution
  - genetic changes in cells that are transferred to offspring

Cellular organization/ same macromolecules



Ten most abundant elements in the Earth's crust

Element	Abundance [% by weight]	Abundance [ppm by weight]
Oxygen	46.1%	461,000
Silicon	28.2%	282,000
Aluminum	8.23%	82,300
Iron	5.63%	56,300
Calcium	4.15%	41,500
Sodium	2.36%	23,600
Magnesium	2.33%	23,300
Potassium	2.09%	20,900
Titanium	0.565%	5,650
Hydrogen	0.14%	1,400

CRC Handbook of Chemistry and Physics, 77th Edition

Elements of life

- **Life accumulates less abundant elements**
  - carbon
  - nitrogen
  - sulfur
  - phosphorus
  - trace elements

TABLE 1-2 Molecular Components of an *E. coli* Cell

	Percentage of total weight of cell	*Approximate number of different molecular species*
Water	70	1
Proteins	15	3,000
Nucleic acids		
DNA	1	1
RNA	6	>3,000
Polysaccharides	3	5
Lipids	2	20
Monomeric subunits and intermediates	2	500
Inorganic ions	1	20

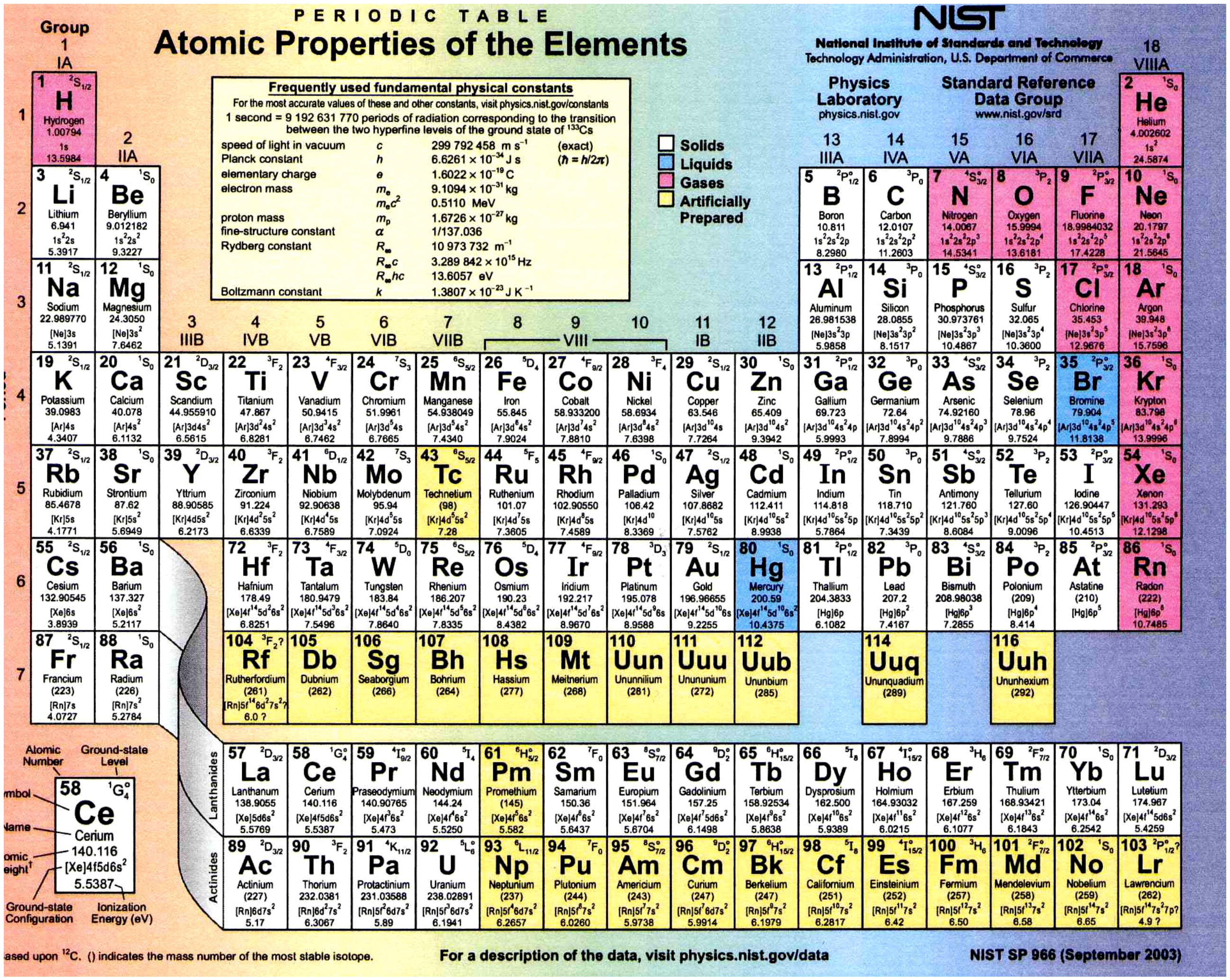
Structure of atoms

- **Atoms are the smallest units of matter that can enter into chemical reactions**
- **Every atom has a centrally located nucleus surrounded by electrons arranged in an *<u>electron configuration</u>***
- **Sub-atomic particles**
  - proton - relative mass: 1; relative charge: +
  - neutron - relative mass: 1; relative charge: none
  - electron - relative mass: 1/1836; relative charge: -
  - # of electrons is equal to the # of protons

Chemical elements

- **Atoms with the same number of protons behave chemically the same way and are classified as the same chemical element**
- **Atomic number** - # of protons
- **Atomic mass** - # of protons + # of neutrons
- **Isotopes** - # of neutrons varies

Periodic table of elements



Electrons

- Electron configuration of an atom
  - how electrons are distributed among the various atomic orbitals (s, p, d, f) and energy levels
- Valence/oxidation state

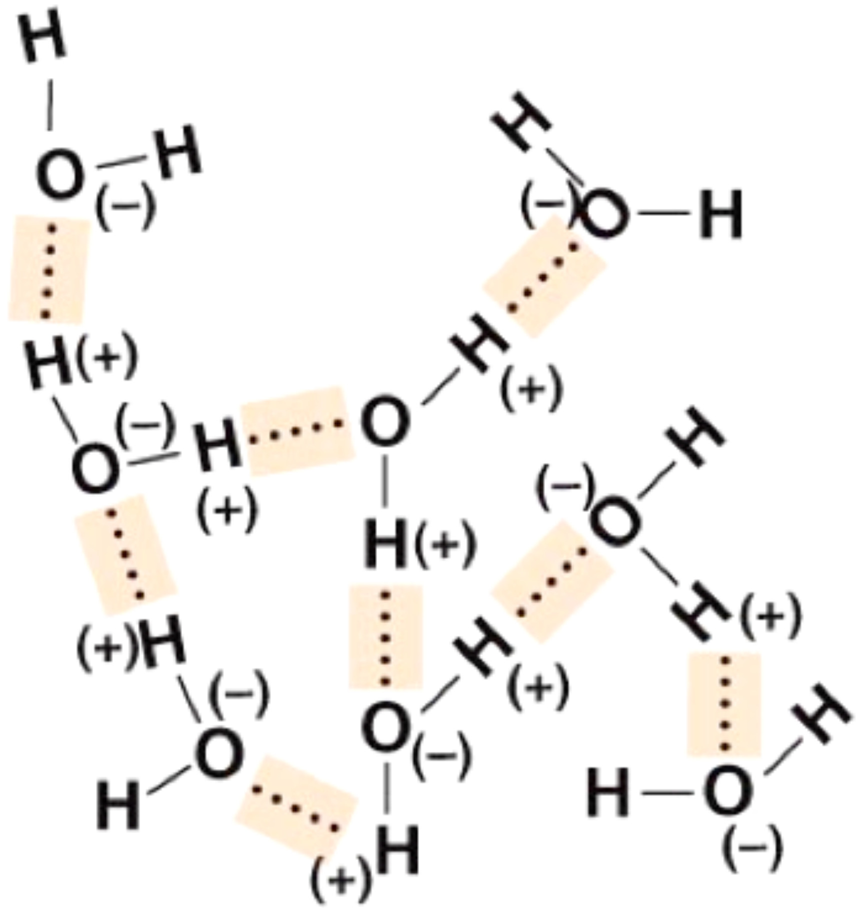
Molecules - compounds

- Reactive atoms form molecules that are held together by chemical bonds
- Molecules with two or more different atoms are called compounds
- Molecular mass
- Monomers
  - small molecules that are the building blocks of larger molecules
  - chemical elements bond in different combinations to form monomers
- Polymers
  - larger molecules composed of bonded monomers
- Macromolecules
  - larger molecules composed of covalently bonded polymers

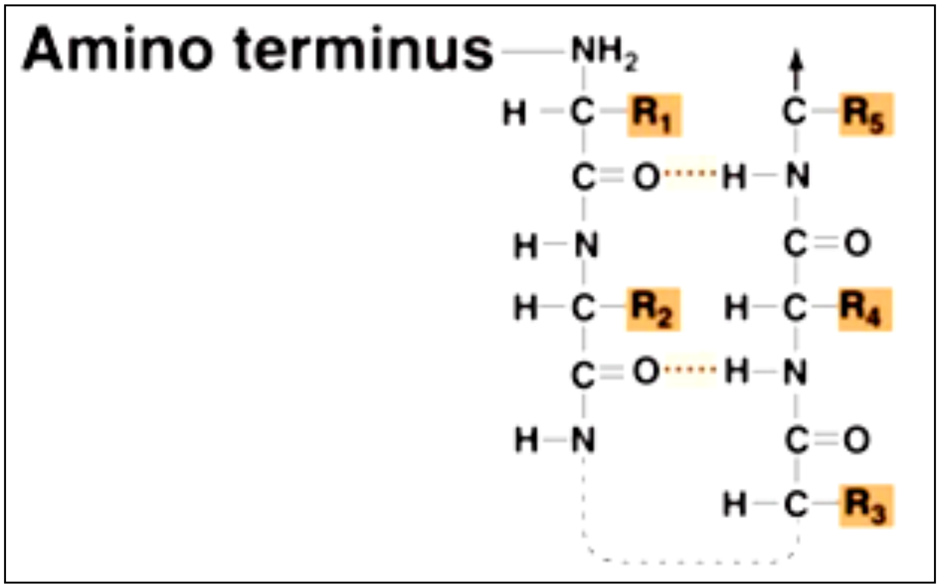
Chemical bonds

- **Ionic bonds**
  - weak pH-dependent electrostatic interactions
  - support ionization in aqueous solutions
  - many important biomolecules (e.g., carboxylic acids, phosphates) are ionized at cytoplasmic pH
- **Covalent bonds**
  - strong bond, two atoms equally share electrons
- **Hydrogen bonds**
  - weak bond formed due to electrostatic interactions between hydrogen atoms and more electron-attracting (*electronegative*) atoms
  - impart considerable stability to molecules
  - play major roles in the biological properties of proteins
- **Van der Waals bonds**
  - weak attractive forces between atoms when they become closer than 3-4 Å
  - play important roles in enzymes binding substrates and protein–nucleic acid interactions

Hydrogen bonds between water molecules



More hydrogen bonds



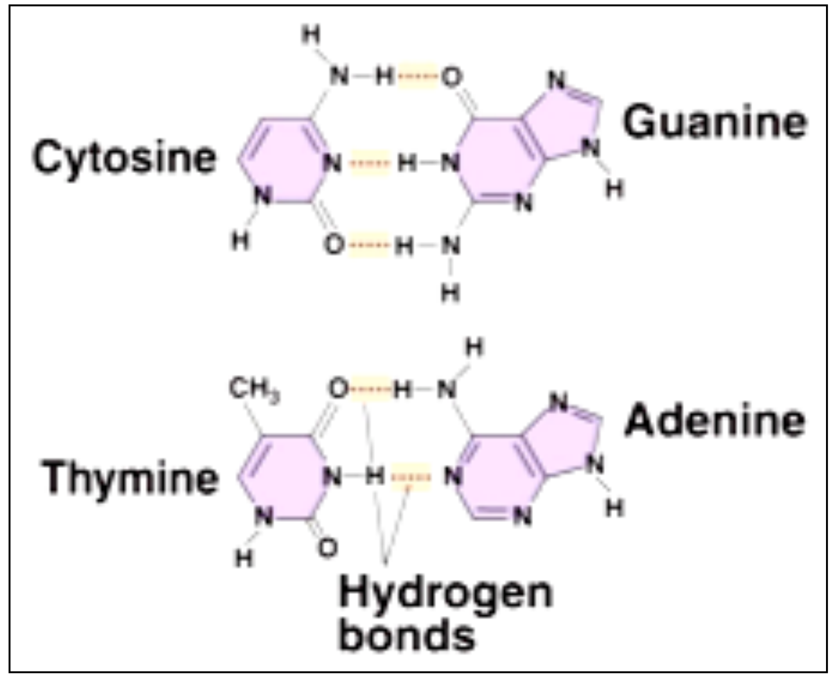


TABLE 1-1 Strengths of Bonds Common in Biomolecules

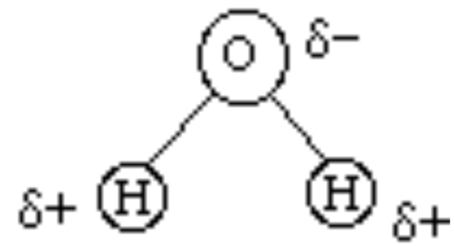
Type of bond	Bond dissociation energy* (kJ/mol)	Type of bond	Bond dissociation energy (kJ/mol)
Single bonds		**Double bonds**	
O—H	470	C=O	712
H—H	435	C=N	615
P—O	419	C=C	611
C—H	414	P=O	502
N—H	389		
C—O	352	**Triple bonds**	
C—C	348	C≡C	816
S—H	339	N≡N	930
C—N	293		
C—S	260		
N—O	222		
S—S	214		

*The greater the energy required for bond dissociation (breakage), the stronger the bond.

Chemical reactions

- **Reaction types of biological importance**
  - synthesis - new bonds are formed
  - decomposition - bonds are broken
  - exchange
- **Reversibility of chemical reactions**
  - energy requirements
    - endergonic and exergonic reactions
  - catalysis/biocatalysis

Biologically important molecules



- **Water**
  - polar molecule - polarity
  - strong bonding between water molecules - cohesiveness
    - high boiling point
    - strong density dependence on temperature
    - water is a solvent
    - water is a reactant or a product
    - water is a temperature buffer

Polarity

- **Polar**
  - possessing hydrophilic (“water-loving”) characteristics
  - generally water soluble
- **Non-polar**
  - possessing hydrophobic (“water-repelling”) characteristics
  - not water soluble

Why is polarity important?

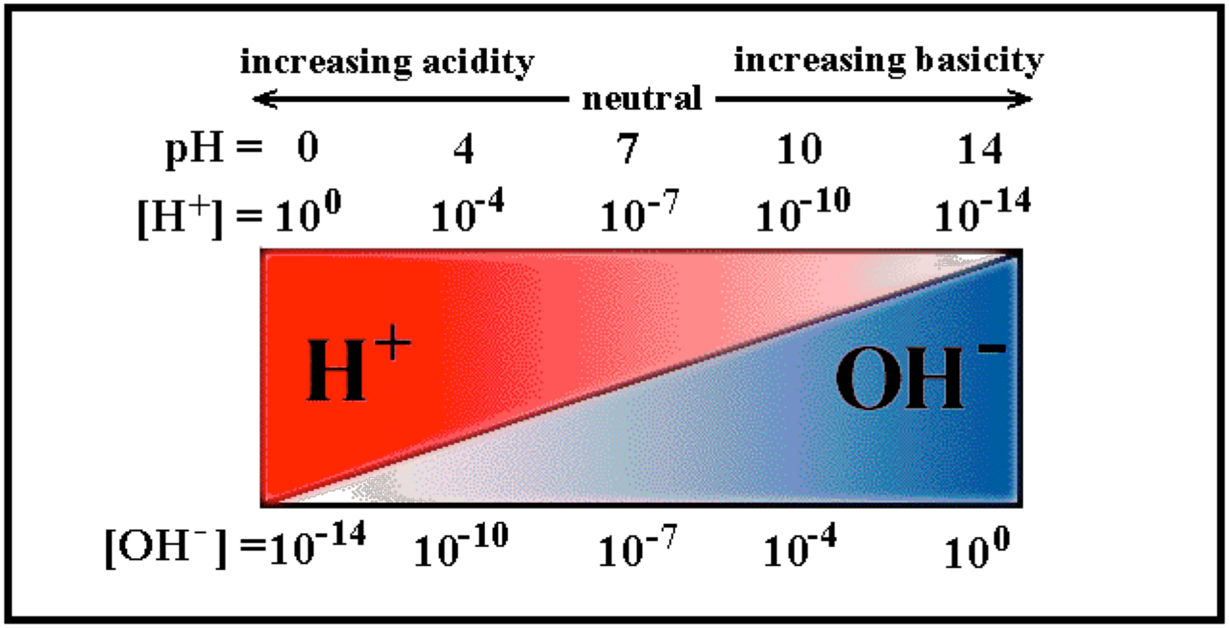
- Many macromolecules are also polar and readily dissolve in water
- Promotes the stability of large molecules through hydrogen bonding
- Forces non-polar substances to aggregate
- Makes water cohesive

Hydrophobic interactions

- Weak bonds
  - non-polar molecules or non-polar regions of molecules associate tightly in a polar environment
- Play important roles in
  - enzymes binding substrates
  - protein conformation
  - stabilization of RNA and cell membranes

Acids and bases

- Acid - can donate a proton (H^+)
- Base - can accept a proton (H^+)
- Salt - cations and anions
- pH
- Buffer - composition that can prevent major pH changes



pH/pOH

- **Measure of hydrogen ion concentration in a solution**
- **$pH = -\log[H^+]$**
- **Example**

  $[H^+] = 0.0001M$,

  $pH = -\log(0.0001) = -(-4) = 4$

Inorganic compounds

- There is no life without water
- Biogeochemical processes
- Electron donors and acceptors
- Metal homeostasis

Organic compounds

- Carbon atoms can combine in an enormous variety of ways
  - carbon skeleton (C, H)
  - functional groups (H, O, N, S, P, *etc*.)
    - their bonding patterns impart unique chemical properties to the compounds
- Monomers build polymers
- Polymers form macromolecules

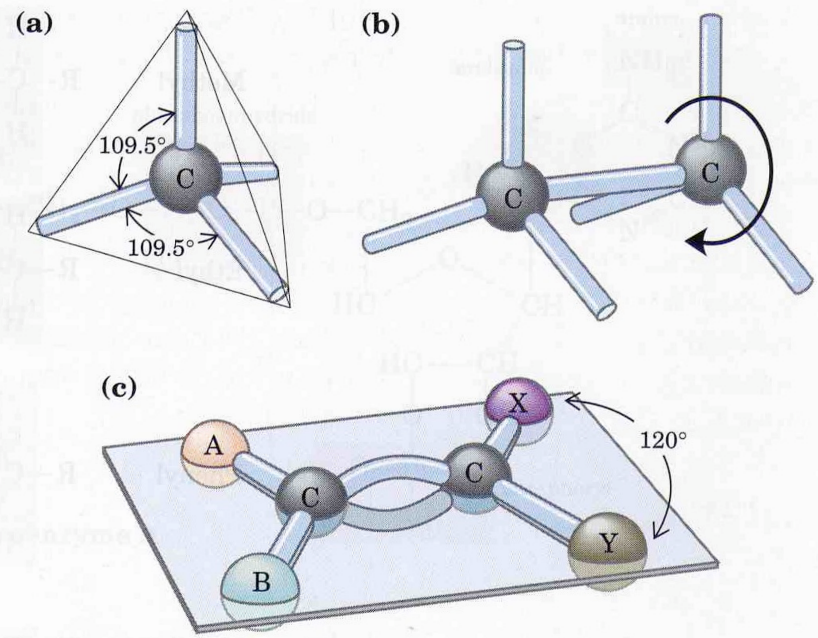


FIGURE 1–14 Geometry of carbon bonding. **(a)** Carbon atoms have a characteristic tetrahedral arrangement of their four single bonds. **(b)** Carbon–carbon single bonds have freedom of rotation, as shown for the compound ethane ($CH_3—CH_3$). **(c)** Double bonds are shorter and do not allow free rotation. The two doubly bonded carbons and the atoms designated A, B, X, and Y all lie in the same rigid plane.

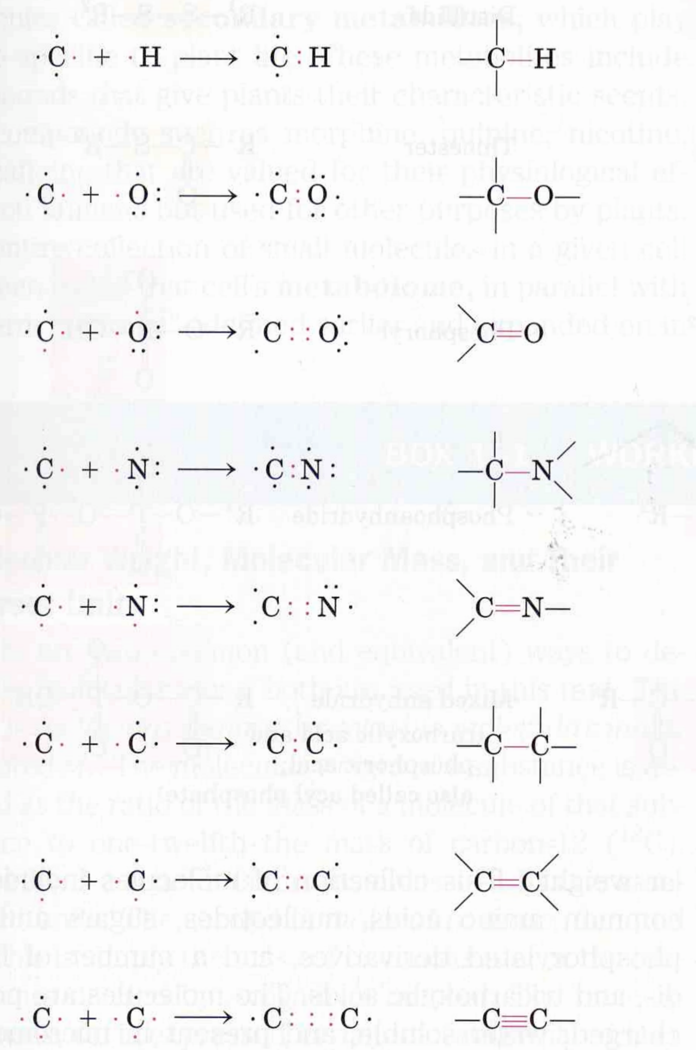
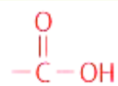
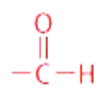
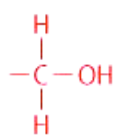
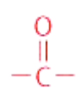
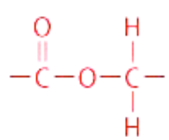


FIGURE 1–13 Versatility of carbon bonding. Carbon can form covalent single, double, and triple bonds (in red), particularly with other carbon atoms. Triple bonds are rare in biomolecules.

Functional groups with biological importance

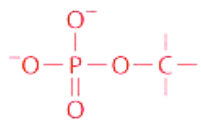
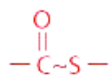
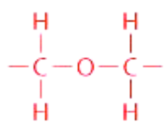
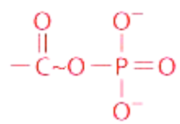
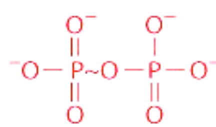
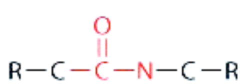
Table 3.1 Some functional groups of biochemical importance

Functional group	*Structure*[a]	*Biological relevance*	*Example*
Carboxylic acid		Organic, amino, and fatty acids; lipids; proteins	Acetate[b]
Aldehyde		Functional group of reducing sugars such as glucose; aldehydes	Formaldehyde
Alcohol		Lipids; carbohydrates	Glucose
Keto		Citric acid cycle intermediates	α-ketoglutarate
Ester		Triglycerides	Lipids of *Bacteria* and *Eukarya*

[a]A squiggle-type bond depiction (~) indicates an "energy-rich" bond (Section 5.8).
[b]Acetate (H_3CCOO^-) is the ionized form of acetic acid (H_3CCOOH).

Functional groups with biological importance

Table 3.1 Some functional groups of biochemical importance

Functional group	*Structure*[a]	*Biological relevance*	*Example*
Phosphate ester		Nucleic acids	DNA, RNA
Thioester		Energy metabolism; biosynthesis of fatty acids	Acetyl-CoA
Ether		Certain types of lipids	Lipids of *Archaea*
Acid anhydride		Energy metabolism	Acetyl phosphate
Phosphoanhydride		Energy metabolism	Adenosine triphosphate (ATP)
Peptide		Proteins	Cellular proteins

[a]A squiggle-type bond depiction (~) indicates an "energy-rich" bond (Section 5.8).
[b]Acetate (H_3CCOO^-) is the ionized form of acetic acid (H_3CCOOH).

Polysaccharides

- Polymers of sugars
  - sugars contain carbon, hydrogen, and oxygen at a ratio of 1:2:1
- Monosaccharides - most biologically relevant contain 4–7 carbon atoms
  - isomers - same molecular formula, but a different arrangement of the atoms in space
    - structural isomers - chain, position, functional group
    - cis/trans isomers (=geometrical isomers)
    - optical isomers (=chiralism)
- Disaccharides
- Oligosaccharides

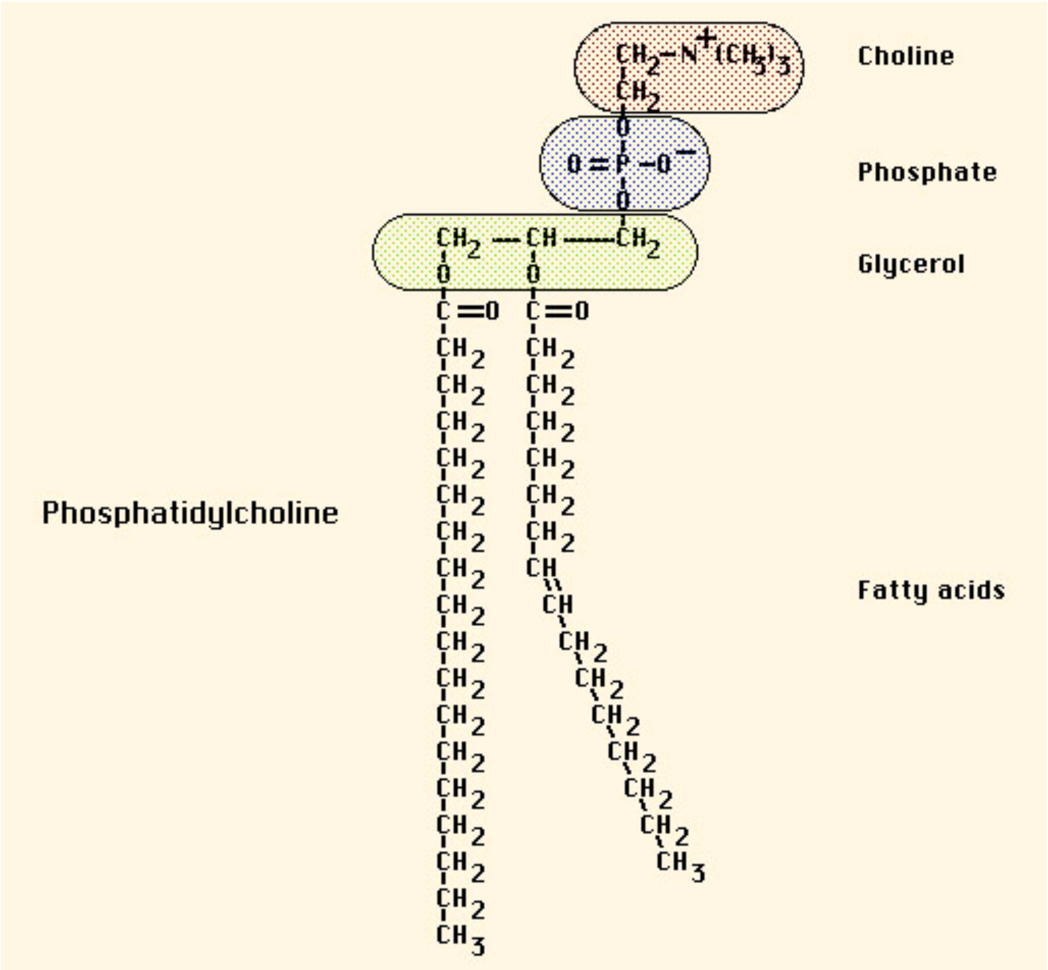
Polysaccharides

- Polysaccharides can combine with other classes of macromolecules to form ***complex*** polysaccharides
  - glycoproteins: polysaccharides + proteins
  - glycolipids: polysaccharides + lipids
  - cellular functions
    - cell-surface receptor molecules - typically reside on external surfaces of the membrane
    - glycolipids important in cell walls of gram-negative bacteria

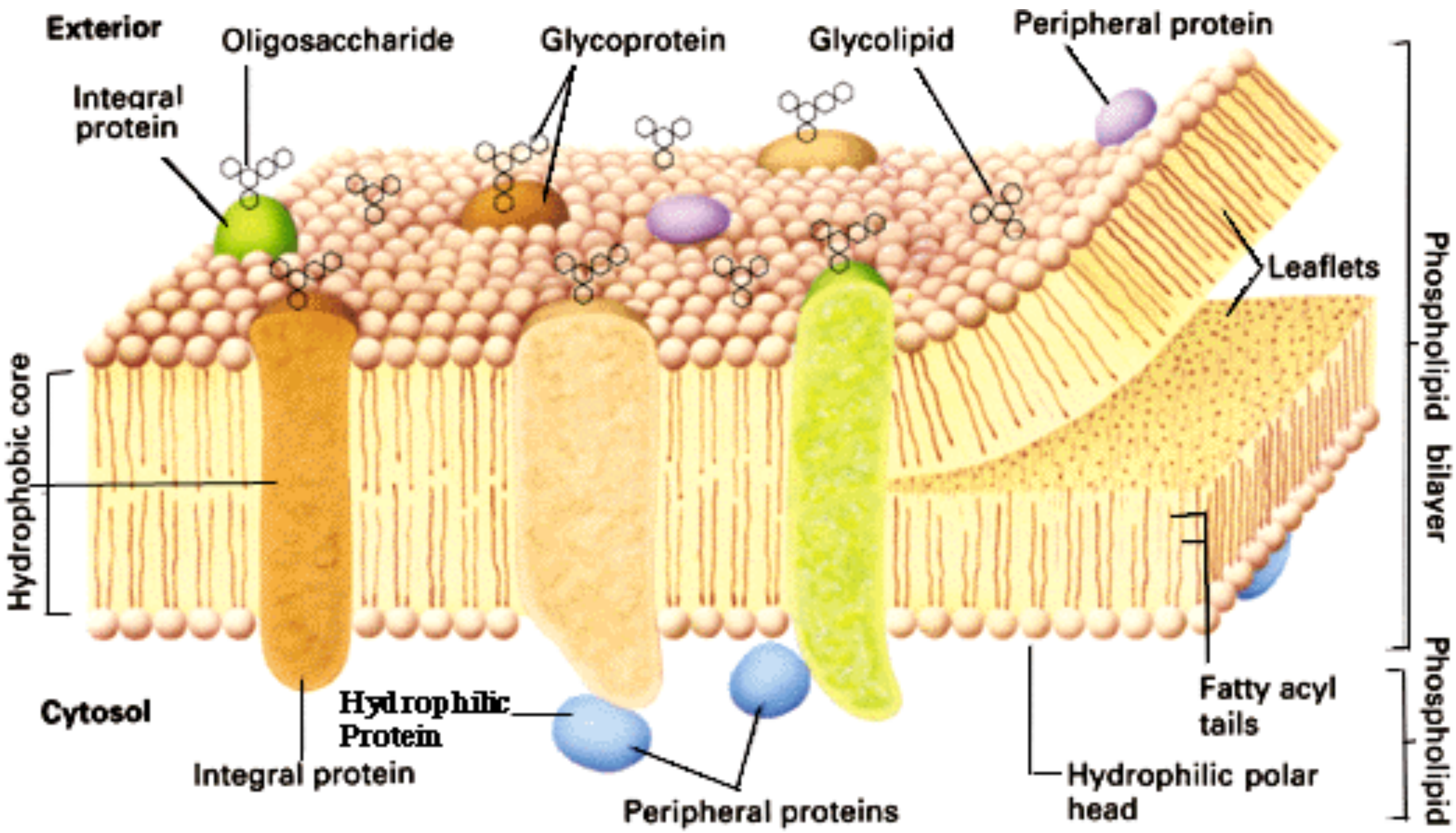
Lipids

- Major group of organic compounds
- Biologically important lipids are amphipathic macromolecules
  - possess hydrophilic and hydrophobic characteristics
- Functions in living systems
  - participate in membranes and cell walls
  - energy storage
- Simple lipids
  - glycerol + fatty acids
  - saturated/unsaturated
- Complex lipids - neutral, polar, non-polar
  - phospholipids
  - steroids and sterols

Phospholipids

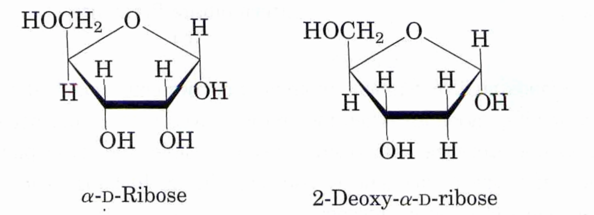


Plasma membrane



Nucleic acids

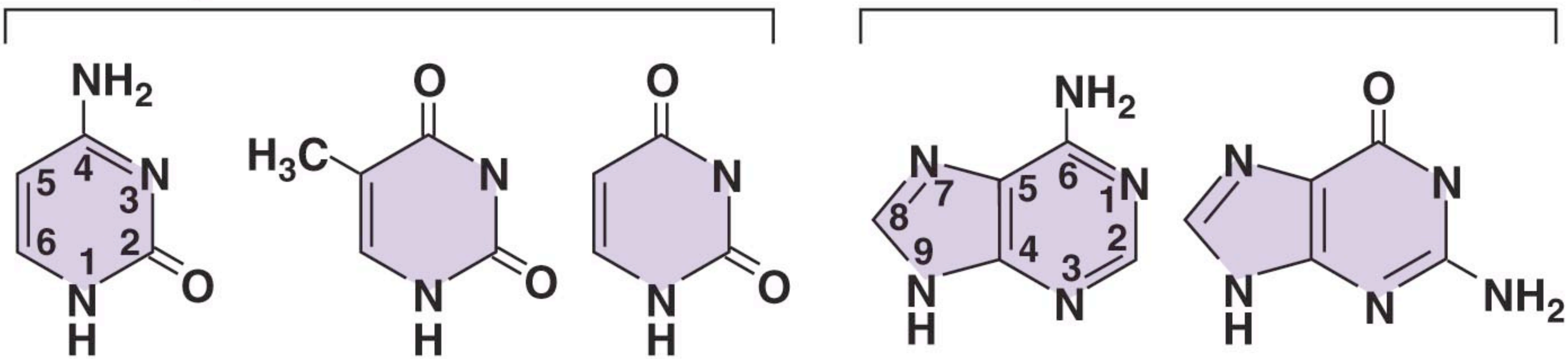
- Deoxyribonucleic acid (DNA)
- Ribonucleic acid (RNA)
- Nucleosides/nucleotides
  - bases
    - purines (adenine and guanine)
    - pyrimidines (cytosine and thymine/uracil)
  - deoxyribose/ribose
  - phosphate group



Five-carbon sugars

Bases in nucleic acids

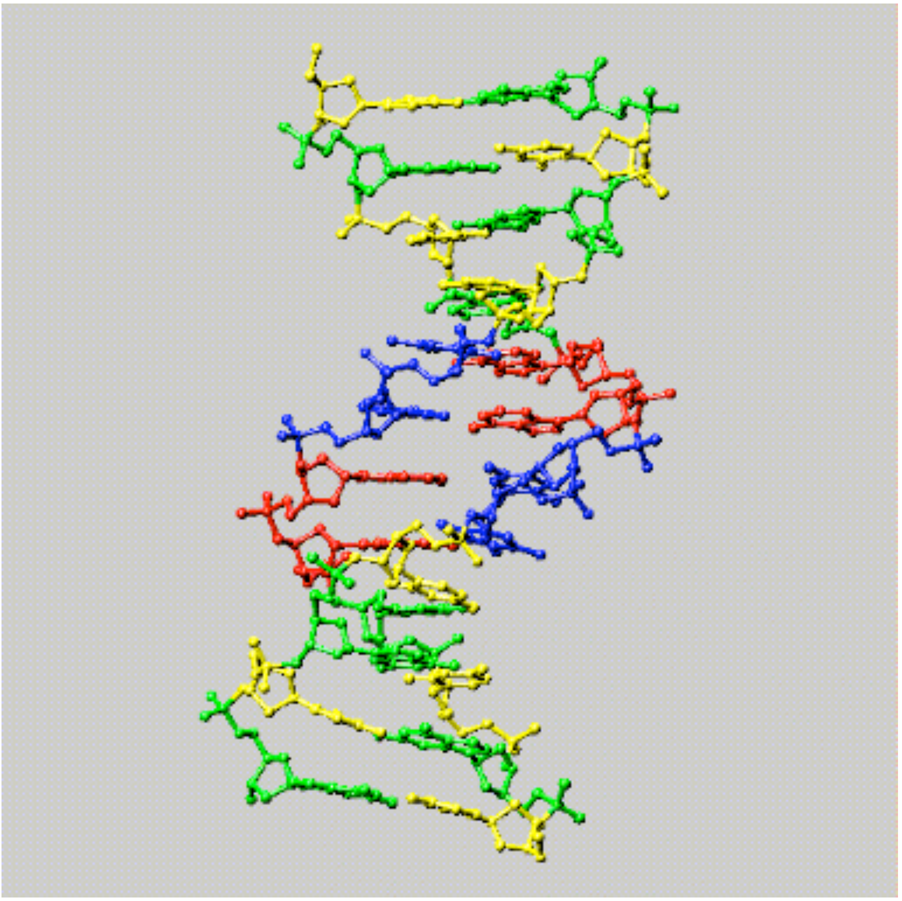
Pyrimidine bases			Purine bases	



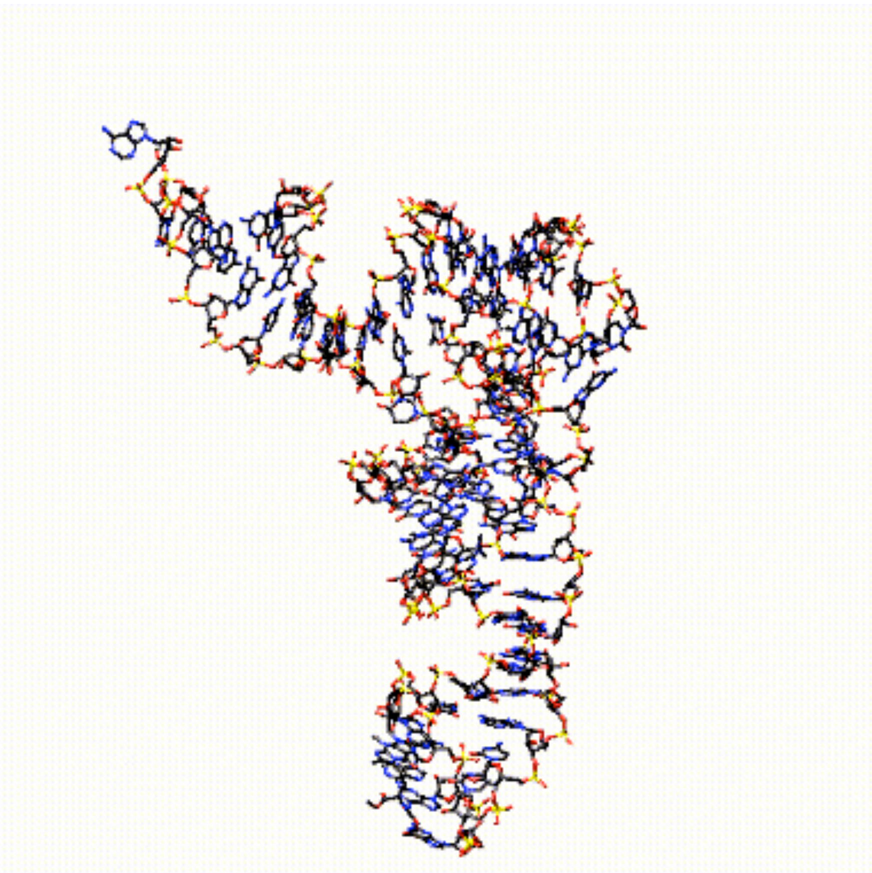
Cytosine (C)	Thymine (T)	Uracil (U)	Adenine (A)	Guanine (G)
DNA RNA	DNA only	RNA only	DNA RNA	DNA RNA

DNA

- Linear polymer of nucleotides
- Nucleotide units connected via the 3' and 5' atoms of two neighboring sugars forming phosphodiester linkages
- Complementary pairing
- Duplex chain is anti-parallel
- Several conformations (B, A, and Z)



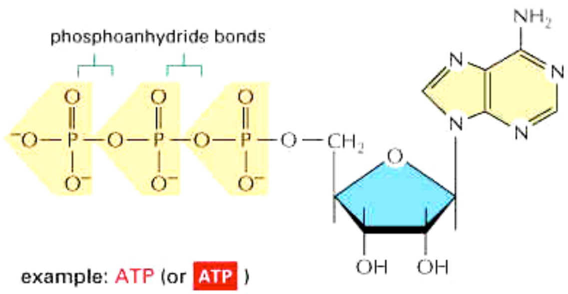
RNA



- Nucleic acid polymer that contains ribose
- Base composition contains uracil (instead of thymine)
- Typically single stranded and forms complex and unusual shapes
- Can form double helix - “A” conformation
- mRNA
- rRNA
- tRNA
- ribozyme
- small RNAs

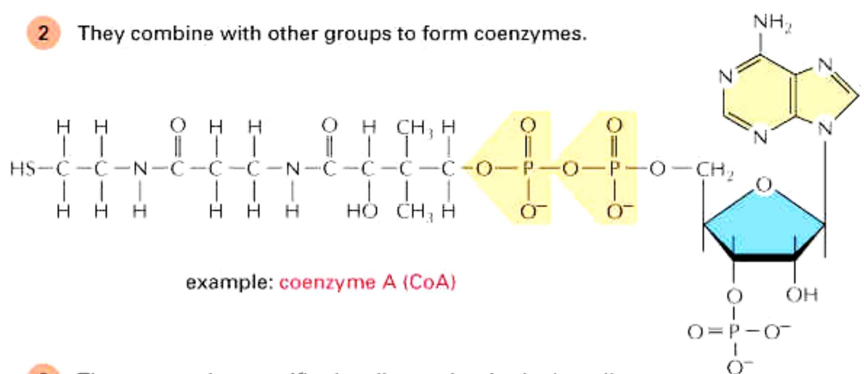
NUCLEOTIDES HAVE MANY OTHER FUNCTIONS

1. They carry chemical energy in their easily hydrolyzed phosphoanhydride bonds.



example: ATP (or ATP)

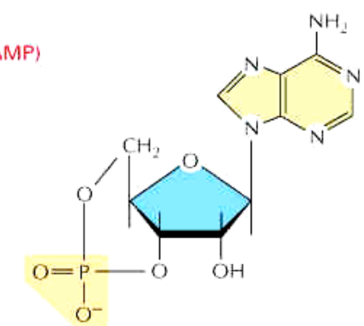
2. They combine with other groups to form coenzymes.



example: coenzyme A (CoA)

3. They are used as specific signaling molecules in the cell.

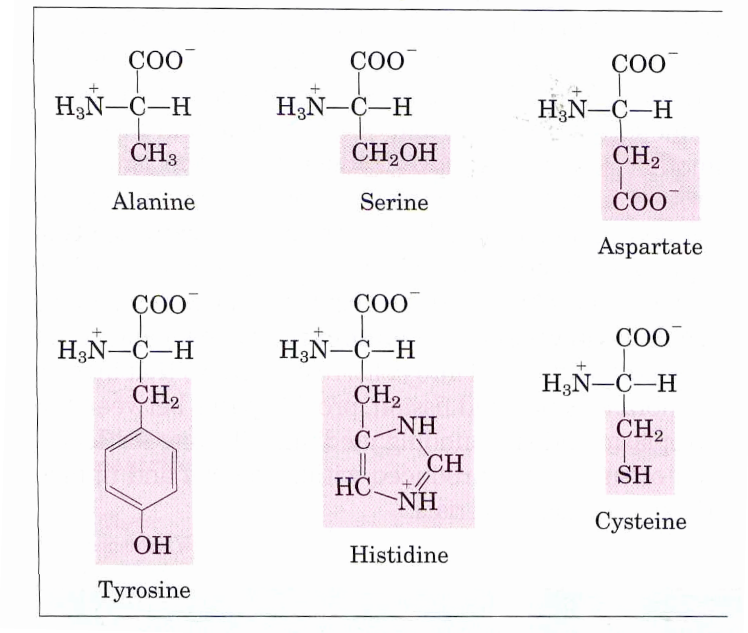
example: cyclic AMP (cAMP)

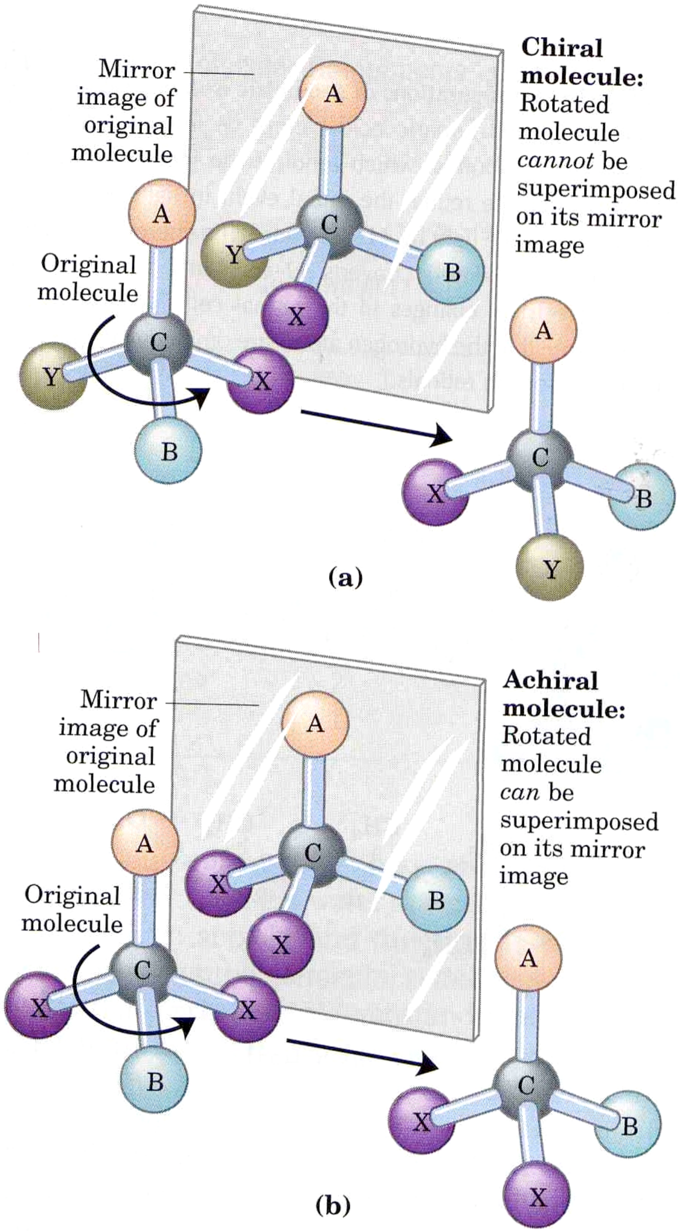


Amino acids

- Building blocks of proteins
- Amino ($-NH_2$) and carboxyl groups ($-COOH$)
- R can be
  - H
  - unbranched or branched chain
  - cyclic or heterocyclic
  - functional groups
- Stereoisomer configuration
- 22 amino acids found in proteins (2 contain sulfur, 1 selenium)

(a) Some of the amino acids of proteins





References and Notes

1. N. P. Kristensen, in *The Hierarchy of Life. Molecules and Morphology in Phylogenetic Analysis*, B. Fernholm, K. Bremer, H. Jörnvall, Eds. (Elsevier, Amsterdam, 1989), pp. 295–306.
2. ———, in *The Insects of Australia*, CSIRO, Ed. (Melbourne Univ. Press, Carlton, ed. 2, 1991), vol. 1, chap. 5.
3. A. H. Staniczek, *Zool. Anz.* **239**, 147 (2000).
4. In June 2001, J. Marshall (Natural History Museum, London) showed O.Z. a male insect from Tanzania, which had been submitted for an opinion 16 years ago. Shortly afterward O.Z. received from F. Kernegger a male Baltic-amber insect (subsequently described as *Raptophasma kerneggeri*), whose close similarity to the Tanzania specimen was immediately obvious. In July 2001, O.Z. discovered in the unsorted alcohol collection of Phasmatodea in the Museum für Naturkunde (Berlin) an adult female of a similar insect from Namibia.
5. According to one school of thought among contemporary systematists, the naming of higher taxa that only contain a single genus is "empty formalism"; we accept the logical merits of this stand. Pragmatically we believe, however, that any recognized genus should be assigned to a "family" and an "order," because these categories play an important role in how biologists communicate and how biological knowledge is systematized.
6. The description includes many characters currently known only from a single specimen, because genitalic characters can only be observed in a specimen of the respective sex, muscle characters can only be observed in the ethanol-preserved female, and only a few characters can be judged in the *Raptophasma* fossils.

Pyrrolysine Encoded by UAG in Archaea: Charging of a UAG-Decoding Specialized tRNA

Gayathri Srinivasan, Carey M. James, Joseph A. Krzycki*

Pyrrolysine is a lysine derivative encoded by the UAG codon in methylamine methyltransferase genes of *Methanosarcina barkeri*. Near a methyltransferase gene cluster is the *pylT* gene, which encodes an unusual transfer RNA (tRNA) with a CUA anticodon. The adjacent *pylS* gene encodes a class II aminoacyl-tRNA synthetase that charges the *pylT*-derived tRNA with lysine but is not closely related to known lysyl-tRNA synthetases. Homologs of *pylS* and *pylT* are found in a Gram-positive bacterium. Charging a $tRNA_{CUA}$ with lysine is a likely first step in translating UAG amber codons as pyrrolysine in certain methanogens. Our results indicate that pyrrolysine is the 22nd genetically encoded natural amino acid.

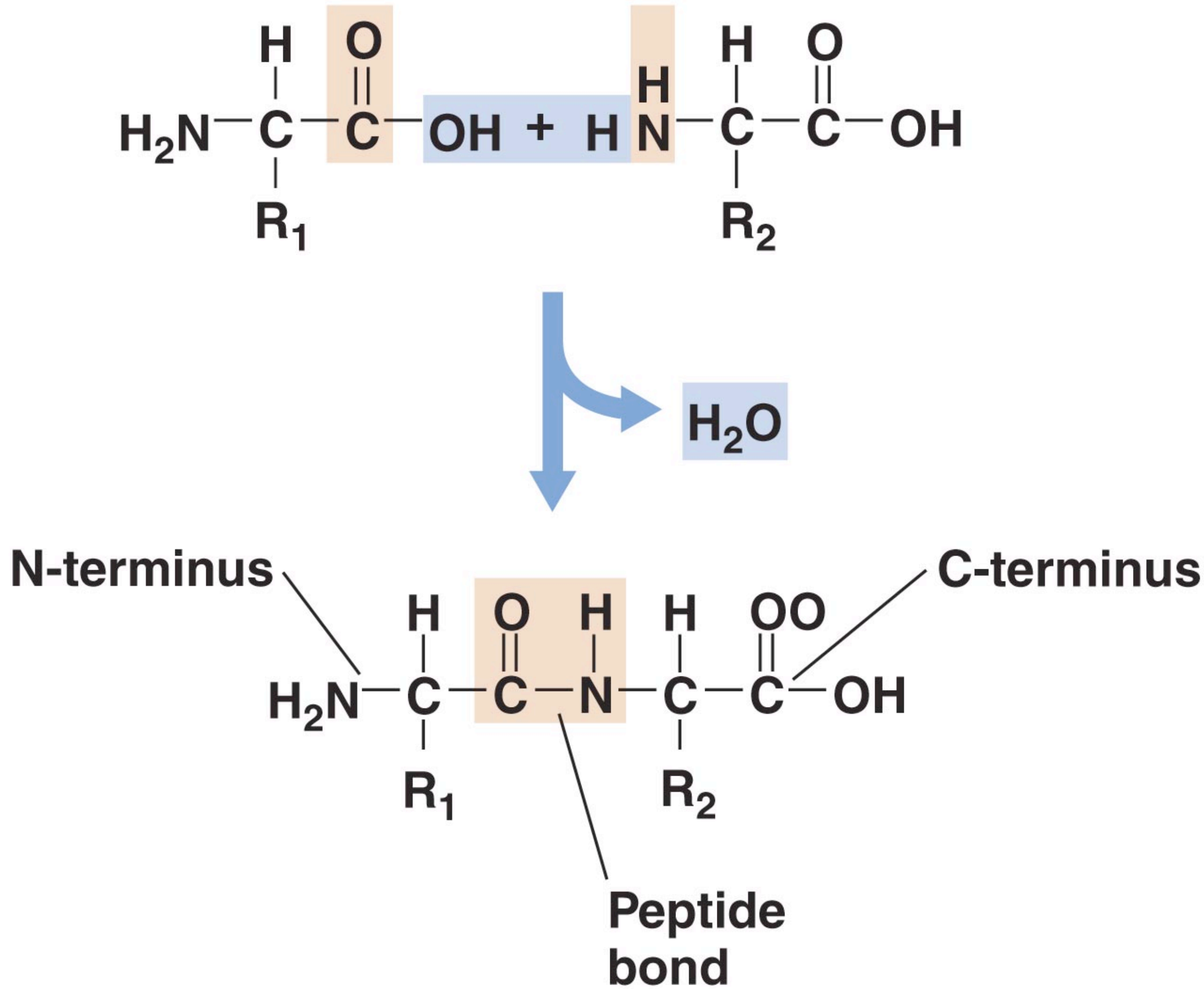
In *Methanosarcina* species, specific methyltransferases initiate methanogenesis and carbon assimilation from substrates such as trimethylamine (TMA), dimethylamine (DMA), or monomethylamine (MMA). The

pool from MMA-grown *M. barkeri* MS revealed an RNA of the size expected for the $tRNA_{CUA}$ product of *pylT* (Fig. 1C). The predicted secondary structure of $tRNA_{CUA}$ has unusual properties compared

Proteins

- Can be more than 50% of cell dry weight
- Essential structures/functions
  - structural proteins (S-layers, cell walls, membranes, cytoskeleton)
  - signal, receptor, and transport proteins
  - regulatory proteins
  - enzymes
  - toxins, antimicrobial proteins
  - in higher organisms hormones, antibodies
- Peptide bonds - covalent bond
- Polypeptides

Peptide bond formation



Protein folding/ structure and function

- **Primary structure**
  - linear array of amino acids in a polypeptide
- **Secondary structure**
  - folds in polypeptide that form a more stable structure, often involving hydrogen bonding between R groups

Protein folding/ structure and function

- Tertiary structure
  - additional folding of polypeptide to result in greater stability and unique three-dimensional shape
  - forms exposed regions or grooves in the molecule that are important for binding other molecules
  - disulfide bonds
    - bonds between -SH groups from two different amino acids

Protein folding/ structure and function

- Quaternary structure
  - occurs in proteins composed of two or more polypeptides
  - subunit
    - each polypeptide in the protein, held together by either/both covalent and non-covalent linkages
  - homodimer
    - protein containing two identical subunits
  - heterodimer
    - protein containing two non-identical subunits